3 Synthesis Assessment of Long-Term Climate Change Technology Scenarios

In order for the Climate Change Technology Program (CCTP) to develop plans, carry out activities and help shape an R&D portfolio that will advance the attainment of its vision, mission and strategic goals, CCTP needs a long-term planning context, informed by analyses from multiple sources and aided by a variety of models and other decision support tools. An important aspect of shaping this planning context is the ability to make assessments of the potential contributions that advanced technologies could make to CCTP strategic goals if their technological potentials are realized.

Such assessments are complex and subject to many uncertainties. They require consideration of a range of assumptions about the future. Specifically, a technology strategy aimed at influencing global GHG emissions over the course of the 21st century would need to consider changing populations, varying rates of regional economic development, differing regional technological needs and interests, and availability of natural resources. In addition, the long-term costs of GHG emission reductions will depend in part on future technological innovations, many of which are presently unknown, and on other factors that could either promote or discourage the use of certain technologies in the future. Finally, both uncertainties inherent in climate science and the fact that value judgments are involved make it difficult to determine a level at which atmospheric GHG concentrations in the Earth’s atmosphere would meet the UNFCCC’s ultimate objective of achieving “stabilization of greenhouse gas concentrations in Earth’s atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system… within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner.”

One approach to planning under such conditions of uncertainty is scenarios analysis. Scenarios present alternative views about the rate of future GHG emissions growth to help gauge the scope of the potential challenge, by methodically and consistently accounting for the complex interactions among economic and demographic factors, energy supply and demand, the advance of technology, and GHG emissions. Scenarios can also investigate feasible pathways to achieving varying levels and schedules of GHG emissions reductions in the future and provide a relative indication of the potential emission reduction benefits of particular classes of technology under a range of different future conditions, and a better understanding of the factors and constraints that might affect the market penetration of these classes of technology. On the other hand, results of scenarios analyses are strongly influenced by a multitude of assumptions and methodological considerations. Scenarios should not be considered predictions.

Many research organizations, university-based teams, government agencies, and other groups have engaged in scenario analysis efforts to explore these topics. This chapter reviews and synthesizes the results of these efforts to gain insights on the scope of the potential technological challenge, the potential contributions of advanced technologies, and to guide CCTP in developing an effective technology development strategy.

3.1 The Greenhouse Gases

Greenhouse gases (GHGs) are those that absorb and emit radiation at specific wavelengths, which causes the “greenhouse effect,” i.e., the trapping of heat in the atmosphere. As shown in Figure 3-1, the GHGs

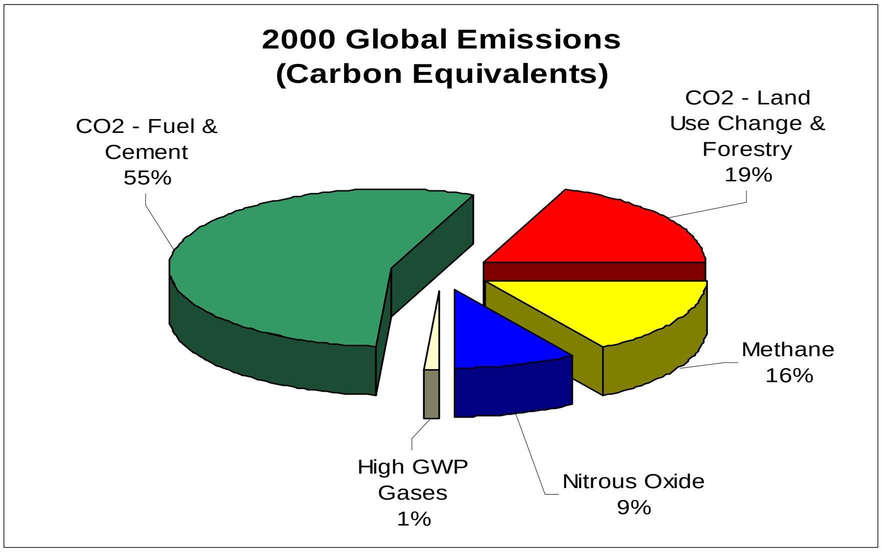

Figure 3-1. Emissions of GHGs in 2000 (% of total GtC-eq.)

Source: http://www.epa.gov/methanetomarkets/docs/methanemarkets-factsheet.pdf

include[1] carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and substances with very high global warming potential,[2] such as the halocarbons and other chlorine and bromine containing substances.[3] CO_2 emissions from the burning of fossil fuels, other industrial activity, and land use change and forestry, account for the majority of GHG emissions. The combined emissions from methane, nitrous oxide, and high-GWP gases accounted for about one-quarter of all GHG emissions (after converting the non-CO_2 gases to a CO_2-equivalency basis, in terms of gigatons carbon equivalent, or GtC-eq.) in the year 2000.

As a GHG resulting from human activities, methane's contribution is second only to CO_2. Methane, on a kilogram-for-kilogram basis, is 23 times more effective at trapping heat in the atmosphere than CO_2 over a 100-year time period. Methane is emitted from various energy-related activities (e.g., natural gas, oil and coal exploration, and coal mining), as well as from agricultural sources (e.g., emissions from cattle digestion and rice cultivation; and waste disposal facilities, landfills and wastewater treatment plants). Methane emissions have declined in the United States since the 1990s, due to voluntary programs to reduce emissions and regulation requiring the largest landfills to collect and combust their landfill gas.[4]

Another important gas is nitrous oxide (N_2O), which is emitted primarily by the agricultural sector through direct emissions from agricultural soils and indirect emissions from nitrogen fertilizers used in agriculture. Aside from CH_4 and N_2O, other non-CO_2 GHGs, including certain fluorine-containing halogenated substances (e.g., HFCs, PFCs, and SF_6), accounted for about 2 percent of total U.S. GHG

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[1] Water vapor and ozone are also GHGs.

[2] Global warming potentials (GWPs) are used to compare the abilities of different greenhouse gases to trap heat in the atmosphere. GWPs are based on the radiative efficiency (heat-absorbing ability) of each gas relative to that of carbon dioxide (CO_2), as well as the decay rate of each gas (the amount removed from the atmosphere over a given number of years) relative to that of CO_2. The GWP provides a construct for converting emissions of various gases into a common measure.

[3] The ozone-depleting halocarbons and other chlorine and bromine containing substances are addressed by the Montreal Protocol and are not directly addressed by this Plan. Besides CO_2, N_2O and CH_4, the IPCC definitions of greenhouse gases include sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs).

[4] See http://www.epa.gov/methane/voluntary.html

emissions in 2003 (EPA 2005). These gases are used or produced by a variety of industrial processes. In most cases, emissions of these fluorine-containing halogenated substances were relatively low in 1990 but have since grown rapidly. The sources of these non-CO_2 GHG emissions are discussed in more detail in Chapter 7.

The heat-trapping capacity of GHGs varies considerably. GHGs also have different lifetimes in the atmosphere. Also, some anthropogenic emissions such as aerosols can have cooling effects. Combining these effects, the Intergovernmental Panel on Climate Change (IPCC) estimated the key anthropogenic and natural factors causing changes in warming (positive radiative forcing[5]) and cooling (negative radiative forcing) from year 1750 to year 2000,[6] as shown in Figure 3-2.

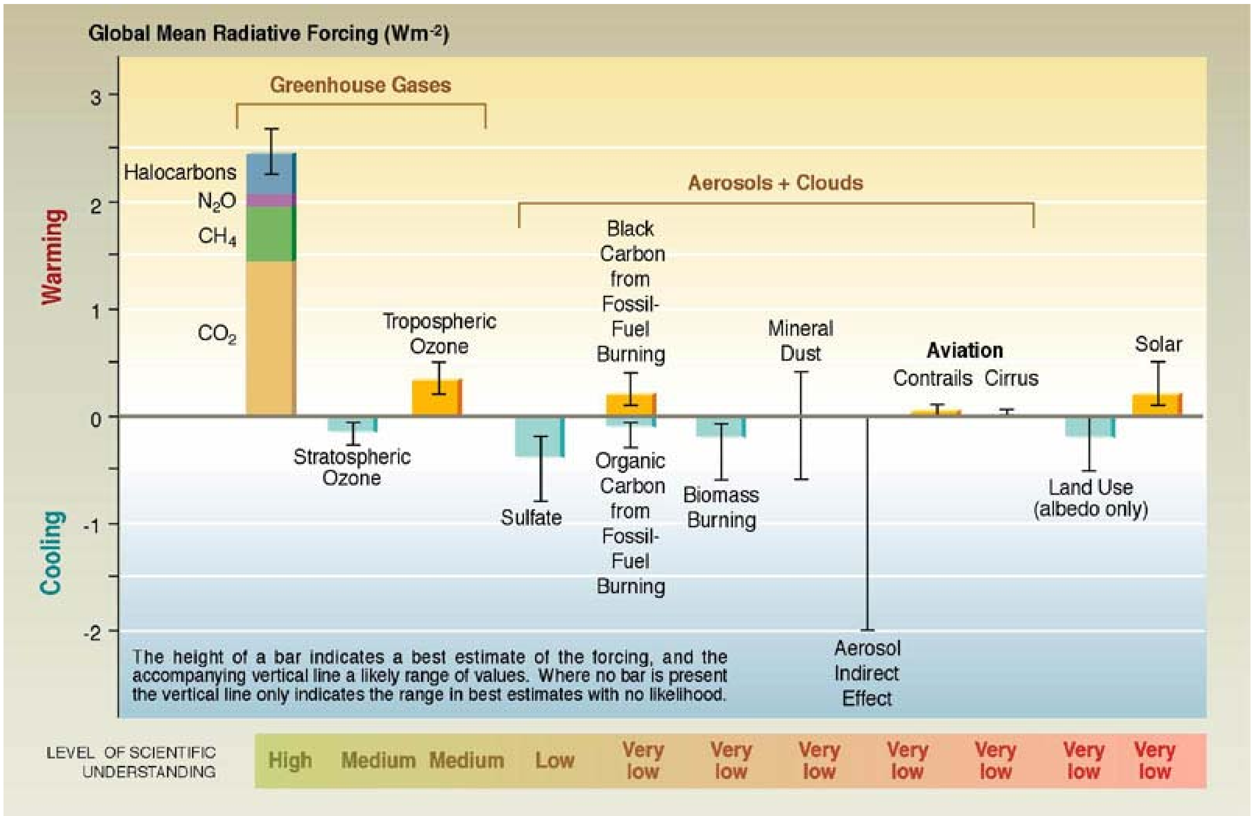

Figure 3-2. Global Mean Radiative Forcing of the Climate System for the Year 2000, Relative to 1750 (*Source: IPCC*[7]*).*

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[5] Radiative forcing is the change in the balance between radiation coming into the atmosphere and radiation going out.

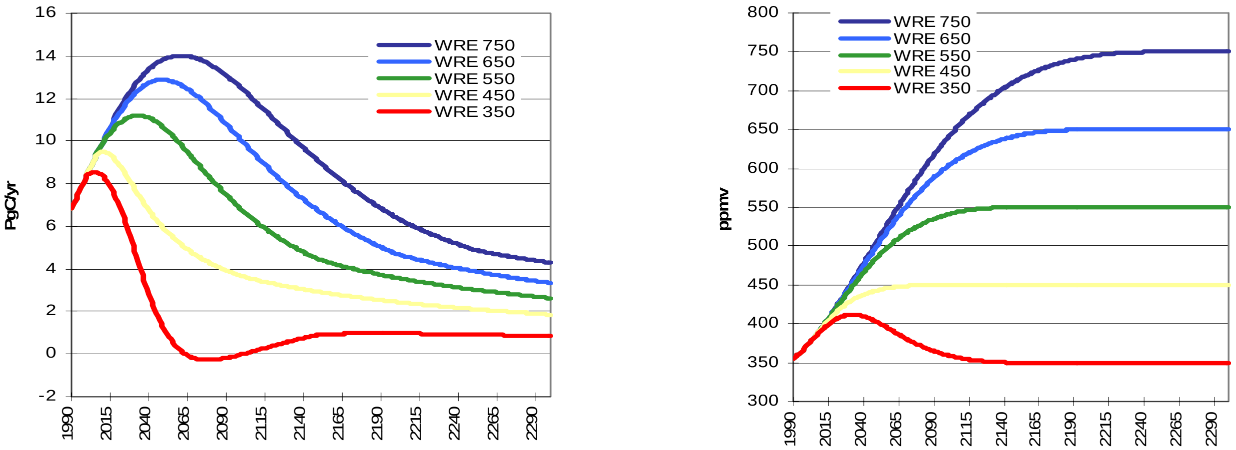
[6] A large body of work has been undertaken to understand the influence of external factors on climate using the concept of changes in radiative "forcing" due to changes in the atmospheric composition, alteration of surface reflectance by land use, and variations in solar input. Some of the radiative forcing agents are well mixed over the globe, such as CO_2, thereby perturbing the global heat balance. Others represent perturbations with stronger regional signatures because of their spatial distribution, such as aerosols. For this and other reasons, a simple sum of the positive and negative bars cannot be expected to yield the net effect on the climate system.

[7] Available at http://www.ipcc.ch/present/graphics/2001syr/large/06.01.jpg

The differences in the characteristics of GHGs and other radiatively important substances, as well as the potential differences in the rates of the growth their emissions over time, influence the formulation of strategies to stabilize overall GHG concentrations.

3.2 Emissions Scenarios Aimed at Stabilizing GHG Concentrations

The scenarios literature has explored the implications of a range of long-term stabilization levels, and various emissions-reduction scenarios have been explored for each stabilization level. Figure 3-3 shows one set of relationships between CO_2 emissions and CO_2 concentrations over time, across a range of CO_2 stabilization levels commonly considered in the scenarios literature.[8] This illustrative set of stabilization levels (Figure 3.3-B) does not include *all* possible stabilization levels that might be consistent with the UNFCCC ultimate objective. In addition, the set of emission curves (Figure 3.3-A) does not represent the only emissions scenarios that could theoretically lead to the corresponding stabilization levels. However, the examples illustrate that emissions trajectories leading the stabilization typically show growth of emissions slowing; and then the emissions eventually peaking, declining and, ultimately, approaching levels that are low or near zero. Uncertainty about the appropriate stabilization levels implies a wide range of possible time periods over which the emissions decrease might occur. Stabilization of CO_2 emissions has been the subject of modeling studies for over a decade. More recently, the multi-gas strategies that consider the possible tradeoffs among GHG emission reductions are being studied (e.g,, see Weyant and de la Chesnaye 2005).



A. Emissions Trajectories from Fossil Fuel Use and Industrial Activities

B. Corresponding Concentration Trajectories

Figure 3-3. Illustrative CO_2 Emissions Profiles and Their Impact on Concentration

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[8] Derived from Wigley et al. 1996. The emissions curves represent net emissions from fossil fuels (i.e., including emissions reductions from carbon dioxide capture and storage) and industrial sources. They do not include emissions from land use and land-use change. The concentration trajectories make specific assumptions regarding net emissions from land use and land-use change, and certain assumptions about the carbon cycle more generally, including assumptions regarding the rate of ocean uptake. Note that significant uncertainties remain about many aspects of the carbon cycle. Optimal emissions paths for fossil fuels and other industrial sources that lead to stabilization could differ from those shown in the figures. Other estimated relationships between emissions and concentrations can be found in the scenarios literature.

3.3 Factors Affecting Future GHG Emissions

Most of the surveyed analyses of future GHG emissions indicate that, in the absence of actions taken to mitigate climate change, increases will occur in both anthropogenic emissions of GHGs and their atmospheric concentrations. The projected rate of emissions growth is dependent on many factors that cannot be predicted with certainty. Widely read studies conducted by organizations, including the IPCC,[9] the Stanford Energy Modeling Forum (EMF),[10] and others,[11] indicate that the more significant factors affecting future GHG emissions growth include demographic change (e.g., regional population growth); social and economic development (e.g., gross world product and standard of living); increases in fossil fuel use; changes in land use; increases in other GHG-emitting activities of industry, agriculture and forestry; and the rate of technological change.

Energy generation and consumption are key determinants of CO_2 emissions. The scenarios with the highest CO_2 emissions are those that assume the highest energy demand along with the highest proportion of fossil fuels in energy production, unless that fossil energy combustion is accompanied by CO_2 capture and storage. Since 1900, global primary energy consumption has, on average, increased at more than two percent/year. The shorter-term trend from 1975 to 1995 shows a similar rate of increase. In the IPCC *SRES* scenarios of the future, 90 percent of the scenarios projected world primary energy use in 2100 to be within the range of 600 to 2800 exajoules (EJ). In 2000, by comparison, total world primary energy use was ~400 EJ. Among the many scenarios surveyed, the average annual growth rates for the century-long period from 2000 to 2100 range from 2.4 percent/year to -0.1 percent/year, with a median value of 1.3 percent/year.[12]

Other organizations, such as the U.S. Energy Information Administration (EIA), make shorter-term projections of total world energy demand. In its most recent projection (EIA 2004), EIA projected world energy demand in its reference case would be 623 EJ/year in 2025. In EIA's work, primary energy use in the developed world is projected to increase by 1.2 percent per year between 2001 and 2025, whereas primary energy consumption in the developing world is projected to grow at an average annual rate of 2.7 percent. Energy use in the emerging economies of developing Asia, which include China and India, is projected to more than double over the course of the quarter century.

At the present time, 1.7 billion people in the world have no access to electricity and 2 billion people are without clean and safe cooking fuels, relying instead on traditional biomass (UNDP 2000). Over the course of the 21st century, a greater percentage of the world's population is expected to gain access to

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[9] A key study that examined emissions growth in the absence of special initiatives directed at climate change is the Special Report on Emissions Scenarios (SRES) by the Intergovernmental Panel on Climate Change (IPCC 2000), in which six of the world's leading energy-economic models were used to explore a suite of scenarios that projected growth in global energy and GHG emissions.

[10] See http://www.stanford.edu/group/EMF/publications/index.htm

[11] See for example, *Direct and Indirect Human Contributions to Terrestrial Carbon Fluxes: A Workshop Summary* (2004) and *Human Interactions with the Carbon Cycle: Summary of a Workshop* (2002), both available from the National Academies Press.

[12] Scenarios that show low or negative energy consumption growth rates over time represent cases where technological improvement is projected to be very rapid and where population and GDP growth rates lie at the lower bounds of the projections.

commercial energy, as well as experience improvements to quality of life, resulting in increased per capita energy use. In addition, world population is expected to grow significantly, which is expected to increase further overall demand for energy.

3.3.1 CO_2 Emissions from Energy Consumption

According to EIA (2004), in the near term (between 2001 and 2025) annual global CO_2 emissions may increase by about 60 percent. For the United States, EIA projects that, by 2025, total CO_2 emissions will increase by 30 percent above the level in 2002. Higher growth rates are expected in the developing regions of the world, where CO_2 emissions may increase by a factor of two or more by 2025. In 2025, global use of petroleum products, primarily in the transportation sector, is expected to continue to account for the largest share of global emissions of CO_2. This is followed in importance by the use of coal, primarily used for electricity generation, and natural gas, which is used for power generation, residential/commercial fuel, and many other uses. Figure 3-4 shows the breakdown of global CO_2 emissions from fossil fuel combustion by end-use sector for 2002.

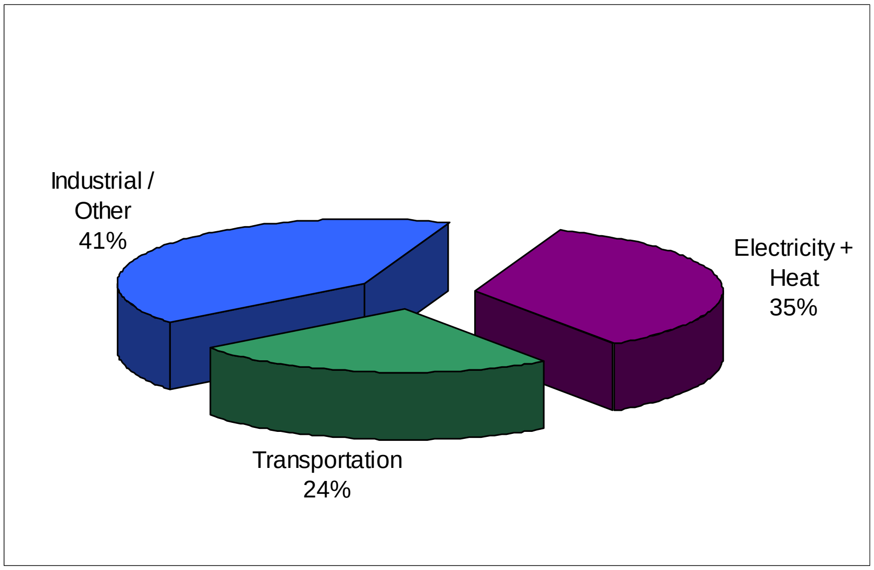

Figure 3-4. Breakdown of CO_2 Emissions from Fossil Fuel Combustion in 2002
(Source: http://www.iea.org/textbase/papers/2005/co2_fact.pdf)

Longer-term projections of CO_2 emissions were compiled during the analysis conducted by IPCC (2000) of multiple reference scenarios from six long-term modeling efforts. This compilation reveals that different assumptions about the driving forces can lead to divergent emissions trajectories. Ninety percent of the CO_2 emissions projections fall within the upper and lower bounds shown in Figure 3-5. The mean, median, and percentage bands shown in Figure 3-5 were calculated based on the range of projections across the full set of scenarios, and do not represent probabilities associated with the projections.

The upper bound is formed by scenario results that assume very high world economic growth, high per-capita energy use, and continued dominance of fossil fuels. At this upper bound, world CO_2 emissions from energy use are projected to grow from about 6 GtC/year in 2000 to more than 30 GtC/year in 2100 – a five-fold increase.

The lower bound in Figure 3-5 is formed by scenarios that assume less population growth, changes in the composition of economic activity away from energy-intensive output, lower per capita energy use, more energy efficiency, and considerably more use of carbon-neutral fuels, compared to the upper bound. At this lower bound, CO_2 emissions are projected to grow for the first half the century, but then to decline to levels about equal to those in 2000–representing no net growth by 2100. Assumptions for the various scenarios are described in Box 3-2.[13] The models used in this study include AIM,[14] ASF,[15] IMAGE,[16] MARIA,[17] MESSAGE,[18] and MiniCAM.[19]

Recent studies have explored the uncertainty in future emissions using a probabilistic approach (see for example, Webster et al. 2002).[20] While there are some differences in the upper and lower bounds of the emissions projections between the SRES scenarios and these more recent probabilistic-based analyses, the range of the SRES scenarios overlaps to a large degree with the range of emissions estimated using these probabilistic approaches.

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[13] The range of CO_2 emissions in the *SRES* has been compared to scenarios done later (post-*SRES*). In general, the ranges are not very different. The estimated CO_2 emissions in post-SRES scenarios have a higher lower bound, a similar median, and a higher upper bound of the distribution. The post-SRES scenarios use lower population estimates, both in range and median. The post-SRES economic development projections (based on market exchange rates) have approximately the same lower bound and median but a lower upper bound of the distribution. A comprehensive database of emissions scenarios is available at http://www-cger.nies.go.jp/cger-e/db/enterprise/scenario/scenario_index_e.html

[14] Asian Pacific Integrated Model (AIM) from the National Institute of Environmental Studies in Japan (Morita et al. 1994).

[15] Atmospheric Stabilization Framework Model (ASF) from ICF Consulting in the USA (Lashof and Tirpak 1990; Pepper et al. 1992, 1998; Sankovski et al. 2000).

[16] Integrated Model to Assess the Greenhouse Effect (IMAGE) from the National Institute for Public Health and Environmental Hygiene (RIVM) (Alcamo et al. 1998; de Vries et al. 1994, 1999, 2000), used in connection with the Dutch Bureau for Economic Policy Analysis (CPB) WorldScan model (de Jong and Zalm 1991), the Netherlands.

[17] Multiregional Approach for Resource and Industry Allocation (MARIA) from the Science University of Tokyo in Japan (Mori and Takahashi 1999; Mori 2000).

[18] Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) from the International Institute of Applied Systems Analysis (IIASA) in Austria (Messner and Strubegger 1995; Riahi and Roehrl 2000).

[19] Mini Climate Assessment Model (MiniCAM) from the Pacific Northwest National Laboratory (PNNL) in the USA (Edmonds et al. 1994, 1996a, 1996b).

[20] There are two ways to approach forecasting the future under uncertainty. One is through the use of scenarios that illustrate different world views or a range of possible outcomes. The second is through uncertainty analysis and probabilistic forecasting. In the latter approach, critical but uncertain parameters (such as demographic or technology trends over time) are identified and quantified through the use of probability distributions. Multiple simulations are performed by sampling from those distributions to construct probability distributions of the outcomes (such as GHG emissions). One can then quantify the likelihood that an outcome falls within a specified range, such as the 90 percent upper confidence limit for CO_2 emissions. In probabilistic approaches to generating emissions scenarios, factors such as labor productivity growth, energy efficiency improvements, agricultural and industrial emissions coefficients for various GHGs, etc. are quantified by expert elicitation or from a review of the literature. These distributions are then used in assessment models to generate a distribution of results such as GHG emissions and/or climate impacts such as temperature change or sea-level rise.

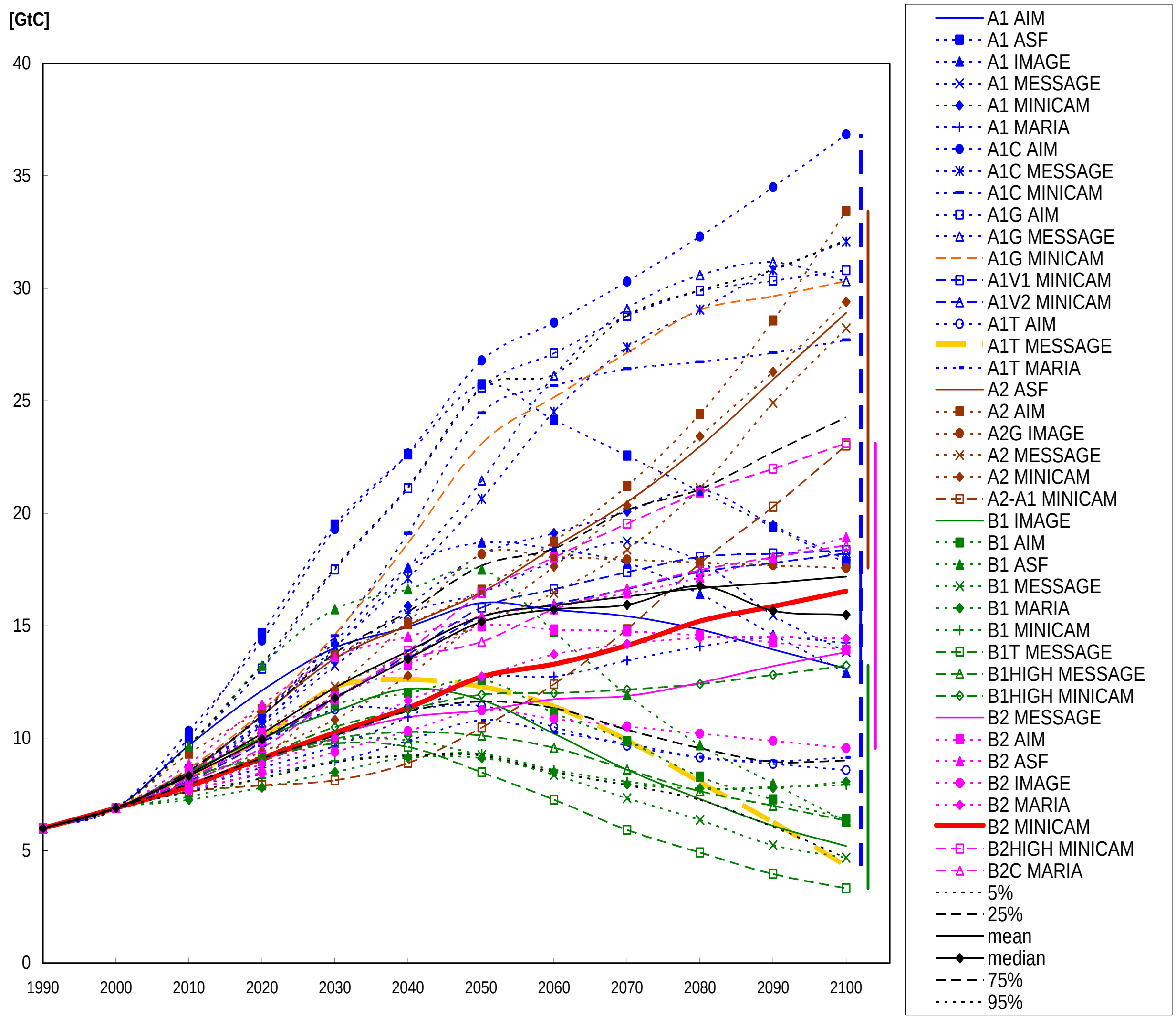

Figure 3-5. Projections of CO_2 Emissions from Energy Use, based on Various Energy-Economic Models and Assumptions

Note: The mean, median, and percentile bands in the figure are based on the range of projections, and do not represent probabilities of the projections.

Box 3-2

The *SRES* Scenarios

The SRES scenarios are organized around four major storylines, which received the names A1, A2, B1, and B2. Each of these storylines represented different general conceptions of how the world might evolve over time, including the evolution of key drivers such as economic growth (including differences or convergence in regional economic activity), population growth, and technological change (see discussion of key drivers from above). Each driver was interpreted by the participating modeling teams in terms of quantitative assumptions about the evolution of specific model parameters. Some scenario drivers, such as economic growth, final energy, and population growth, were harmonized across many of the models, while others, such as the specific technology assumptions, were developed by the individual modeling teams to be generally consistent with the storylines. For the A1 Scenario, four basic assumptions about technology were also developed, so there are four categories of technology scenarios under the A1. The scenarios are described as follows:

A1. The A1 storyline and scenario family describe a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The four A1 groups are distinguished by their technological emphasis: fossil intensive (A1C – coal- and A1G – gas), non-fossil energy sources (A1T), or a balance across all sources (A1B), where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies.

A2. The A2 storyline and scenario family describe a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in a continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than in other storylines.

B1. The B1 storyline and scenario family describe a convergent world with the same global population, which peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline and scenario family describe a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than in A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

The set of harmonized drivers depended both on the scenario and the specific model. Key drivers that characterized the scenarios are summarized qualitatively in the table below. Comparison of the emissions trajectories in Figures 3-5 and 3-6 can be interpreted in terms of the relative evolution of these drivers and the discussion of these drivers above.

	A1						
Driver	**A1C**	**A1G**	**A1B**	**A1T**	**A2**	**B1**	**B2**
Population Growth	low	low	low	low	high	low	medium
GDP Growth	very high	very high	very high	very high	medium	high	medium
Energy Use	very high	very high	very high	high	high	low	medium
Land-Use Changes	low-medium	low-medium	low	low	medium/high	high	medium
Availability of Conventional and Unconventional Oil and Gas	high	high	medium	medium	low	low	medium
Pace of Technological Change	rapid	rapid	rapid	rapid	slow	medium	medium
Direction of Technological Change Favoring:	coal	oil & gas	balanced	non-fossils	regional	efficiency & dematerialization	"dynamics as usual"

3.3.2 CO_2 Emissions and Sequestration from Changes in Land Use

CO_2 emissions in the future will be influenced not only by trends in CO_2 emissions from energy use and industrial sources, but also by trends in land use that result in either CO_2 sequestration or a net increase in CO_2 emissions. CO_2 emissions and carbon sequestration associated with various land uses will be driven primarily by increasing demand for food, as well as other factors, such as demand for wood products, land management intensity, demand for biomass energy and bio-based products, and technological change.

The role of land-use change has received relatively limited consideration (compared to energy use) in prior modeling exercises aimed at developing long-run GHG emissions scenarios. To date, the most comprehensive treatment is contained in the scenarios developed for the IPCC *SRES* (IPCC 2000). In developing these scenarios, the IPCC assembled a data base of over 400 earlier emissions scenarios. Of these, 26 scenarios (all the work of three modeling groups) explicitly considered the role of land-use change on global CO_2 emissions. Differences in methodology, assumptions, and base period made comparisons of the scenarios difficult. Most of the scenarios show net global CO_2 emissions from land-use change decreasing to below current levels by 2100, with some scenarios indicating net sequestration (Figure 3-6).

A key insight to emerge from the IPCC exercise was that the link between land-use change and global CO_2 emissions is much more complex and much more uncertain than had been reflected in previous emissions scenarios. Across and within the four storylines described in Box 3.2, the scenarios produced a wide range of land-use paths that included large increases and decreases in the global areas of cropland, grassland, and forest over periods of 50 and 100 years.

In general, scenario differences in land-use patterns resulted from alternative assumptions about population and income growth (via the demands for food, meat, and environmental goods). The scenarios indicate that land-use change could be either an important source or sink of global CO_2 emissions over the next 100 years, depending on the mix of goods and services the world's population demands from its land resources. The future paths of technological change in today's land-intensive sectors—including agriculture, forestry, energy, construction, and environment quality—will help to define the role of land-use change. Many of the IPCC scenarios show that CO_2 emissions from deforestation are likely to peak after several decades and then subsequently decline.[21]

More recently, Sohngen and Mendelsohn (2003) linked global forestry models with global energy models to more explicitly explore the relationships between land-use management, land-use emissions, and global energy systems. They report a net sequestration potential of about 18 GtC in global forests, in the absence of human intervention, and suggest there might be less deforestation in tropical regions than the IPCC *SRES* study projected.

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[21] This pattern is tied to declines in the rate of population growth toward the latter half of the century and increases in agricultural productivity.

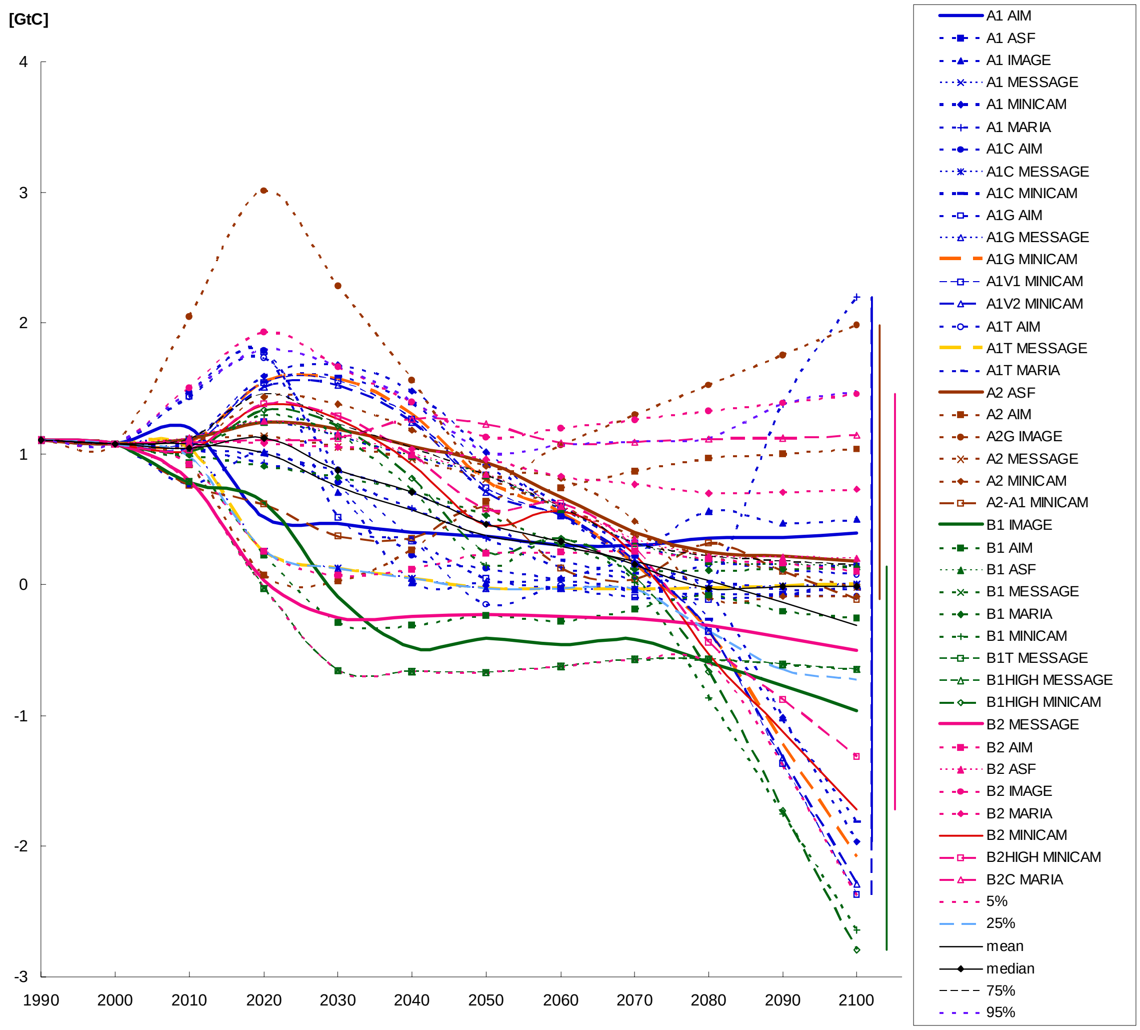

Figure 3-6. Net CO_2 Emissions from Land Use Change (Source: IPCC 2000)[22]

Note: The mean, median and percentile bands in the figure are based on the range of projections, and do not represent probabilities

3.3.3 Other Greenhouse Gases

As discussed in Section 3.1, the non-CO_2 GHGs include a diverse group of gases such as methane, nitrous oxide, chlorofluorocarbons and other gases with high global warming potential. Future growth in emissions of non-CO_2 GHGs will depend on the future level of the activities that emit these gases, as well as the amount of emissions control that occurs. Cost-effective emissions controls will depend on the trade-offs (based on relative cost and climate impact) in mitigating different GHGs.

Integrated assessment models have only recently begun to project long-term trends in non-CO_2 GHGs. In a recent international modeling exercise conducted by the Stanford Energy Modeling Forum, non-CO_2 emissions and mitigation potential were projected by 18 models of various forms (Weyant and de la

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[22] The structure of the underlying modeling exercise required harmonization in 2000. Such harmonization in the context of a modeling exercise does not necessarily reflect agreement.

Chesnaye 2005).[23] Each model ran a “reference case” scenario, in which non-CO_2 GHGs were allowed to grow in the absence of any constraints or incentives for GHG emissions mitigation.[24]

The results for methane and N_2O are shown in Figures 3-7 and 3-8, respectively. The projections vary considerably among models. On average, non-CO_2 GHGs were projected to increase from 2.7 gigatons of carbon equivalent emissions (GtC-eq) in 2000 to 5.1 GtC-eq in 2100. On average, methane emissions were projected to increase by 0.6 percent/year between 2000 and 2100; nitrous oxide by 0.4 percent/year; and the fluorinated gases by 1.9 percent/year. (By comparison, in these same scenarios, CO_2 emissions were projected to grow by 1.1 percent/year over the same time period—see Weyant and de la Chesnaye 2005.)

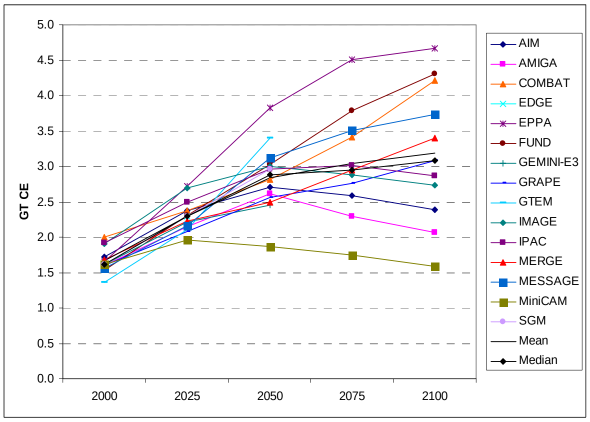

Figure 3-7 Methane Emissions Projections from the EMF-21 Study, With No Explicit Initiatives to Reduce GHG Emissions

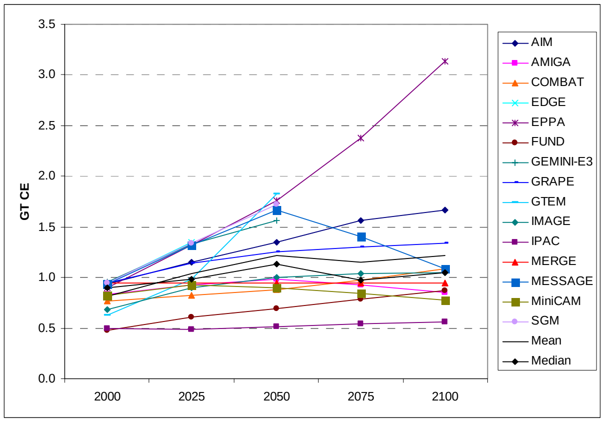

Figure 3-8. Nitrous Oxide Emissions Projections from the EMF-21 Study, With No Explicit Initiatives to Reduce GHG Emissions

3.4 Implications for CCTP Planning

For the purposes of CCTP planning and analysis, it is useful to understand the potential contributions of advanced technologies to GHG emissions reductions over a century-long planning horizon. Although the specific stabilization path for attaining the UNFCCC objective is not known, and none is assumed, modeling the general parameters of such a hypothesized challenge across many different paths can provide useful information about a range of technologies that might contribute. This may be illustrated by one such example, shown in Figure 3-9. To meet the stabilization level in this hypothetical example, annual GHG emissions would have to be reduced by about 13 GtC-eq in 2100 from the level of an otherwise “unconstrained” illustrative case.[25] For the example shown, the cumulative emissions reduction

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[23] The models included a variety of model types, including integrated assessment models and general equilibrium models.

[24] Note, however, that some of the models (such as MiniCAM) project that some GHG-reducing technologies penetrate the market without incentives or policies. For example, methane emissions from coal and natural gas production would penetrate the market when it is cost effective to do so, based on the value of the methane (natural gas) collected, which can be used as a fuel.

[25] The “unconstrained” case in this illustrative example is based on the reference scenario developed for CCTP by PNNL; see Placet et al. (2004). The lower curve representing emissions leading to stabilization is based on the 550 ppm trajectory shown in Figure 3-3A; for more information, see Wigley et al. (1996).

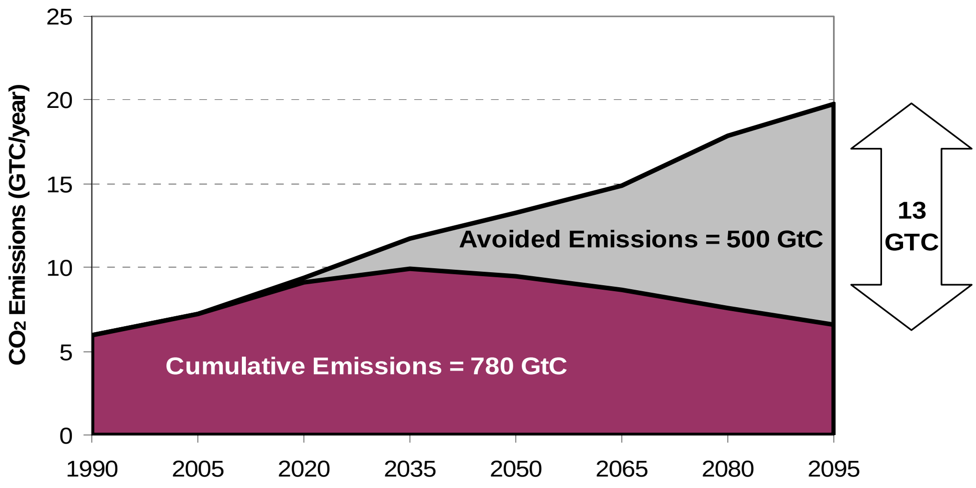

Figure 3-9. Potential Scale of CO_2 Emissions Reductions to Stabilize GHG Concentrations: Hypothetical Unconstrained and Reduced-Emissions Scenarios

over the course of the 21st century, when compared to a case with unconstrained emissions growth, would be approximately 500 GtC-eq. For various other stabilization and baseline trajectories, the cumulative emissions reductions ranged from 200GtC-eq to 800 GtC-eq.

The curves shown in Figure 3-9 represent but one of many potential emissions reductions scenarios. Many combinations of constrained and unconstrained emissions trajectories are conceivable, and many combinations of GHGs could potentially contribute to the total GHG reduction. In general, the lower the stabilization level, the larger the reduction in both CO_2 and non-CO_2 GHGs that would be required.

The specific roles of non-CO_2 GHGs would depend on factors such as the stabilization level, timeframe to stabilization, and the characteristics of the GHGs themselves (e.g., atmospheric lifetime and global warming potential). In particular, scenarios have approached methane emissions reductions in distinctly different ways because of its relatively short lifetime in the atmosphere.[26]

The example in Figure 3-9 shows a hypothetical stabilization situation that results in annual emissions reduction of about 13 GtC from the reference scenario by the year 2100. Box 3-3 provides illustrations of measures that could achieve an annual reduction of one GtC-eq/year. As the examples suggest, the technologies would have to be implemented on a significant scale. The costs of achieving such reductions using today's technology could be high. The implication for CCTP and its associated science and technology R&D programs is to develop more efficient and less costly technologies, including novel or breakthrough technologies, that could significantly reduce GHG emissions, while maintaining economic growth and ensuring safety and overall environmental quality.

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[26] Methane is generally reduced earlier in models based on GWP conversions, because its reduction is relatively less costly than reducing emissions of other GHGs. In optimization models based on radiative forcing, methane reductions are pushed back toward the point in time at which stabilization is achieved. This is because methane emitted prior to the decade immediately preceding the target would not affect the radiative forcing at the target date, because it would have already broken down in the atmosphere.

Box 3-3

How Big is a Gigaton of GHG Reduction?

Actions that provide 1 Gigaton/year of carbon-equivalent mitigation for the duration of their existence:

Coal-Fired Power Plants. Build 1,000 “zero-emission” 500-MW coal-fired power plants. Current global installed generating capacity is about 2 million MW.

Geologic Sequestration. Install 3,700 sequestration sites like Norway’s Sliepner project (0.27 MtC/year)

Nuclear. Build 500 new nuclear power plants, each 1 GW in size. This would more than double the current number of nuclear plants worldwide.

Electricity from Landfill Gas Projects. Install 7,874 “typical” landfill gas electricity projects (typical size being 3 MW projects at non-regulated landfills) that collect landfill methane emissions and use them as fuel for electric generation

Efficiency. Deploy 1 billion new cars at 40 miles per gallon (mpg), instead of new cars at 20 mpg

Wind Energy. Install new wind capacity to produce 150 times the current U.S. wind generation

Solar Photovoltaics. Install new solar energy capacity to produce 10,000 times the current U.S. solar PV generation

Biomass Fuels from Plantations. Convert a barren area about 15 times the size of Iowa’s farmland (about 33 million acres) to biomass crop production

CO_2 Storage in New Forest. Convert a barren area about 40 times the size of Iowa’s farmland to new forest

Notes:

- All reductions for power technologies are measured relative to new coal-fired plants without CO_2 capture and storage)
- Many of these examples are adaptations from Pacala and Socolow (2004).

3.5 The Role of Technology

Reducing GHG emissions on the scale hypothesized in Section 3.4 could be achieved in many ways. It is unlikely that any single technology would be able to achieve the level of GHG emissions reductions that are likely to be required to stabilize GHG concentrations in the atmosphere. Given the diversity of the energy sector and potential constraints on the availability of resources, achieving reductions on such a scale will almost certainly require contributions from a combination of existing, improved or transitional, and advanced technologies.

The projected contribution of any technology depends in large part on assumptions about the success of scientific and technical advancements, among other factors. These types of factors are examined routinely in scenario analyses. For example, in the mitigation scenarios studied in the IPCC Working Group III,[27] as well as studies performed as part of EMF-19 (for example, van Vuuren et al. 2004 and Manne and Richels 2004), lower-carbon fuels (e.g., natural gas) and technologies such as integrated gas combined-cycle were projected to bridge the transition to more advanced fossil and zero- or low-carbon

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[27] http://www.grida.no/climate/ipcc_tar/wg3/084.htm

technologies. A theme common to many mitigation scenarios is a steady improvement in energy efficiency, as is the emergence of biomass as an important energy source throughout the next century.

In addition to technical considerations, cost considerations also are a major element of mitigation scenarios. Once the decline in costs makes them economically attractive, low-carbon-emitting technologies play a major role in many scenarios. Different technologies may mature and become cost-competitive at different times over the course of the 21st century. For example, increased energy efficiency (using today's technologies), mitigation of non-CO_2 GHGs, and terrestrial sequestration may be the more cost-effective options in the nearer term, while transformative supply-side and end-use technologies with greatly reduced GHG emissions could become commercially viable later, as technology development progresses.

Several landmark multi-model scenarios analysis studies,[28] as well as various scenarios analysis efforts based on individual models, have explored emissions reduction scenarios. Advanced technology scenarios are sometimes modeled against a range of hypothetical GHG emissions constraints (e.g., low, medium, high, and very high). The results of these, in turn, can be compared against a series of reference or baseline scenarios, where the given GHG emissions constraints are met, but with different assumptions about the advancement of technology and costs. These hypothetical results can suggest what might be possible if assumptions about technology advancement could be realized.

3.5.1 Alternative Advanced Technology Emission Reduction Pathways

A number of approaches can be pursued to explore the potential contributions of advanced technologies. One of the more direct approaches is to focus on a particular technology or genre of technology and estimate what could be achieved if it were to be fully adopted by a certain time in the future. For example, Brown et al. (1996) estimated the amount of mitigation that could be achieved with single technologies. More recently, Pacala and Socolow (2004) discussed technology "wedges," each of which represent the mitigation of one gigaton of carbon emissions in the year 2050 (see some examples in Box 3-2, some of which were adapted from Pacala and Socolow). Hoffert et al. (2002) examined technologies needed to deliver a certain amount of carbon-free energy by the end of the 21st century. Such assessments are useful for understanding the maximum technical potential of various technologies.

In reality, however, advanced technologies would need to meet a complex array of conditions before they could be successfully implemented. For instance, they would need to be cost-competitive in the market, compared to other available technologies. Other considerations include ease of use, reliability, public safety and acceptance, and policy, environmental or regulatory factors. Taking these considerations into account requires a more complex approach. Models are typically used to evaluate the competition among technologies to meet required emission reduction targets or react to various emissions taxes or policies. Such models typically simulate the deployment of technologies and approaches that could achieve a given amount of emissions reductions at the lowest cost in a given time period. If the technical potential of such technologies meets the required emissions reduction assumed in the scenario, these low or no-cost approaches may supply a large portion of the emissions reduction.[29] More costly, but feasible, advanced

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[28] For example, the IPCC "Post-SRES" report on Mitigation (IPCC 2001) and the EMF studies (Weyant 2004).

[29] The suite of technologies in the first category generally includes improvements to current systems and energy conservation–the so-called "no-regrets" strategies. Such improvements, often modeled as a general rate of energy-efficiency (or intensity) improvement, are often included in the business-as-usual (or "reference case") emissions projections.

technologies come into play more extensively in scenarios that require moderate to high levels of emissions reduction. Expensive, undeveloped, or undemonstrated technologies or others that may face non-cost barriers may enter the market later in the mitigation period. Hence, the mix of technologies in any given scenario depends on many assumptions about the costs, technical readiness, and barriers to implementation for each type of technology.

One scenarios analysis, recently completed by Pacific Northwest National Laboratory (PNNL), explored three advanced technology scenarios, each of which was designed to achieve a range of GHG emissions reductions (Placet et al. 2004).[30] The three advanced technology scenarios include:

- Scenario 1, which assumes successful development of fossil energy technologies with carbon capture and storage and high-efficiency fossil energy conversion
- Scenario 2, which assumes technological improvement and cost reduction of carbon-free energy sources such as renewable energy (wind power, energy from bio-sources, and other solar energy systems) and nuclear power
- Scenario 3, in which major advances in fusion energy and novel energy applications for solar and advanced biotechnology are assumed to occur[31]

Figures 3-10 and 3-11 provide illustrative results across the three scenarios for the high emissions constraint case. Figure 3-10 shows the contributions, over the course of the 21st century, of various energy sources to total global energy demand under the three advanced energy scenarios. Figure 3-11 shows the emissions reduction contributions from the various energy sources and technologies.

Although each scenario assumes advances in one particular class of technology, all scenarios result in a mix of energy efficiency and energy supply technologies. These results, as with the others, show the variation possible in the mix of emissions-reducing technologies under a variety of assumptions and planning uncertainties.

3.5.2 Economic Benefits of Advanced Technologies

A primary purpose of CCTP is to accelerate the advancement of promising technologies and reduce their cost. The more economically competitive of these technologies will, under the right conditions, enter the marketplace and contribute to reduced GHG emissions. They might also achieve the same emissions reductions at costs significantly lower than would be the case had they not been developed or made available.

In the aforementioned analysis by PNNL (Placet et al. 2004), the estimated costs of achieving a range of emission reductions were compared for cases with and without the use of advanced technology. The resulting cost estimates (Figure 3-12) show that the present values of the cumulative costs for meeting the hypothetical carbon constraints were significantly lower in all three advanced technology scenarios than

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[30] This study was conducted for the US CCTP.

[31] In the PNNL study, Scenarios 1, 2 and 3 are called “Closing the Loop on Carbon,” “A New Energy Backbone,” and “Beyond the Standard Suite.” Also note that all three scenarios assumed significant improvements in end-use efficiency.

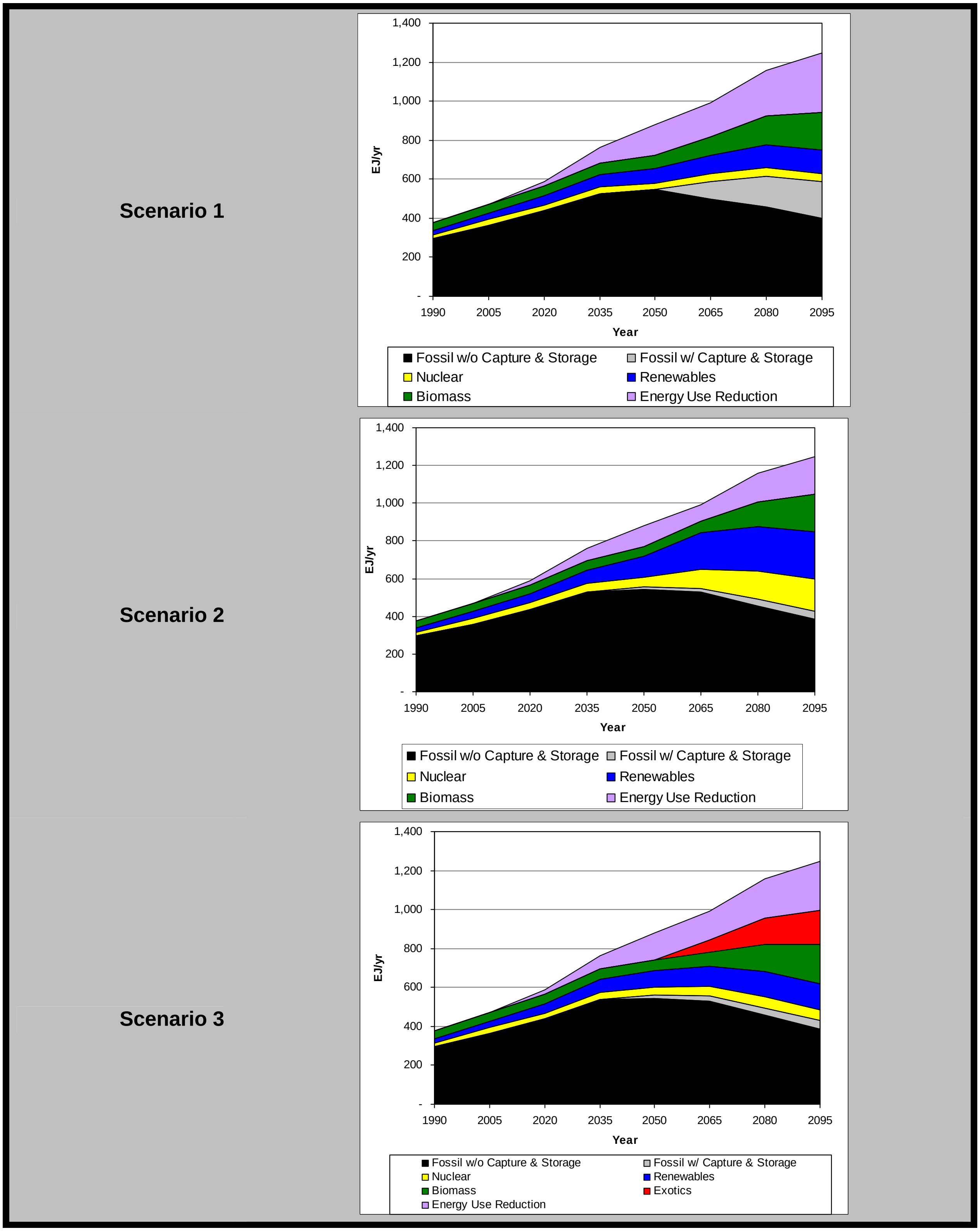

Figure 3-10. World Primary Energy Demand (Source: Placet et al. 2004)

Note: "Energy Use Reduction" is the amount of energy conserved or saved through advanced energy-efficient end-use technologies compared to a reference case, which also includes a considerable increase in energy efficiency compared to today's level. See the cited reference for more detail.

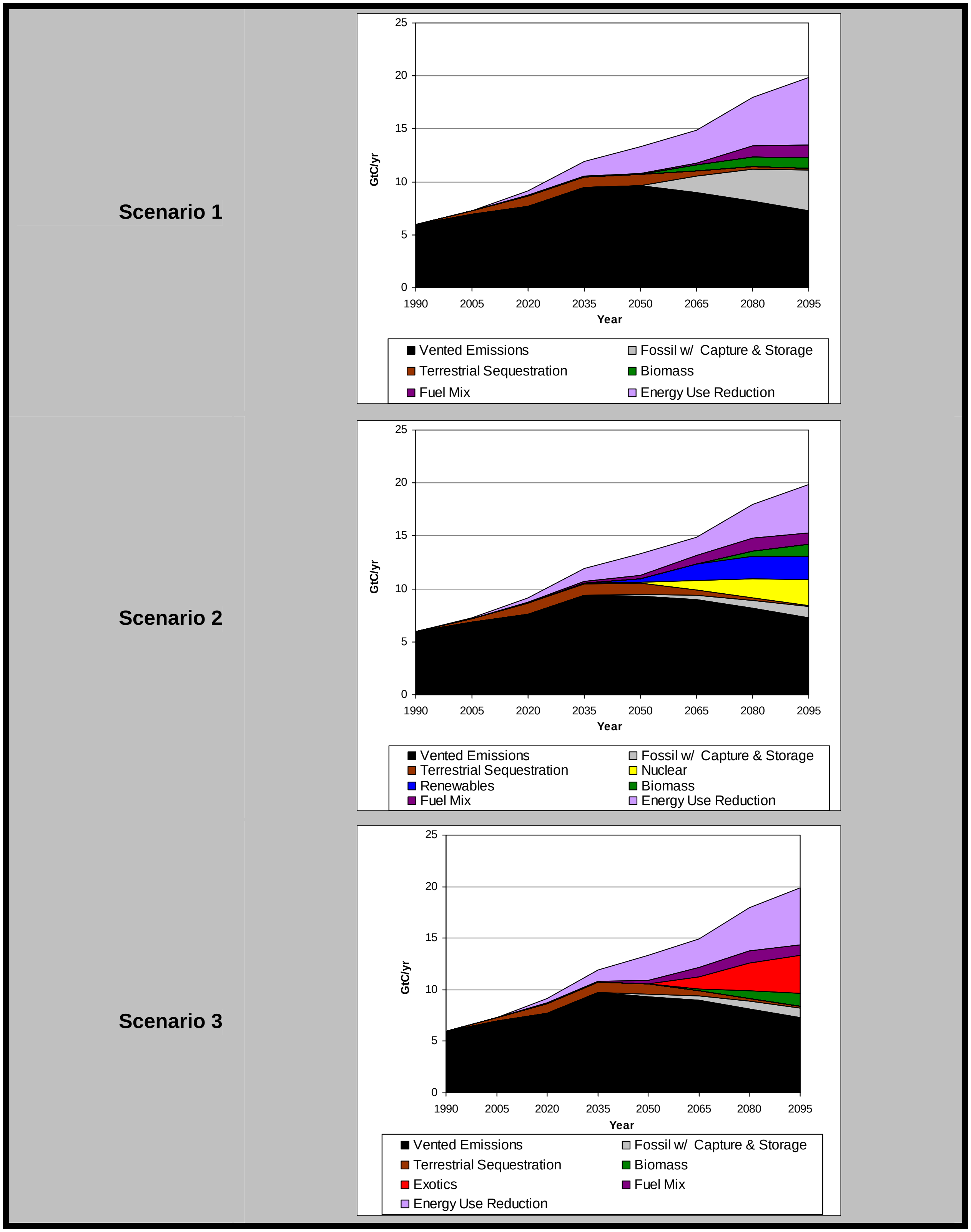

Figure 3-11. World Carbon Dioxide Emissions: Released (Vented) and Mitigated (Source: Placet et al. 2004)

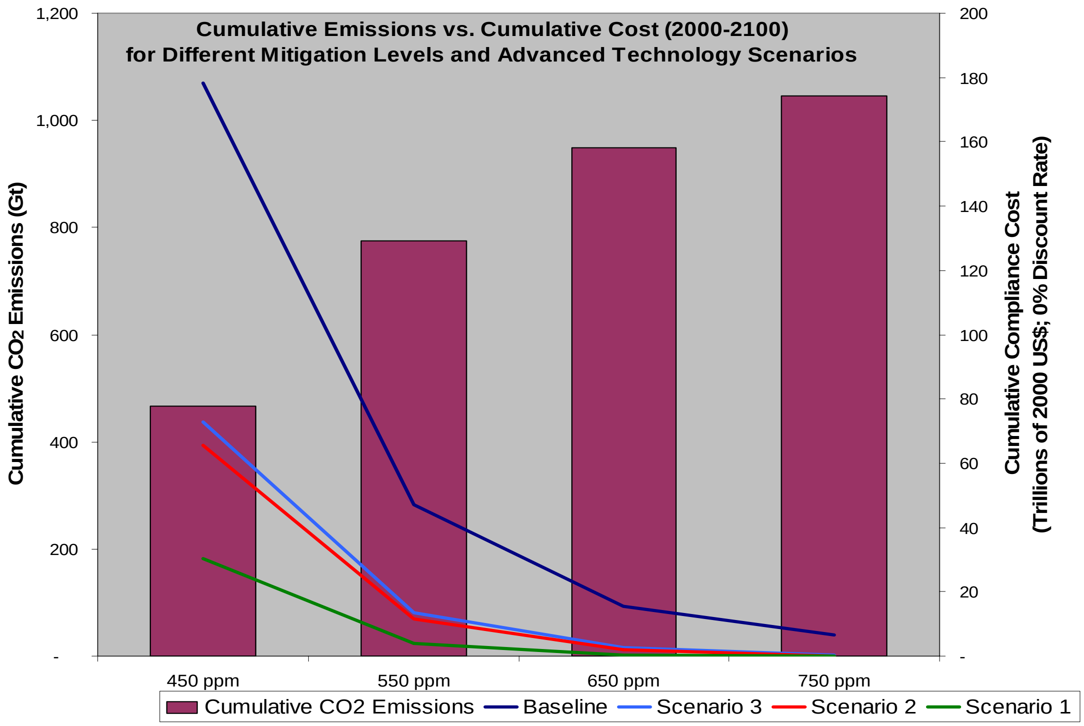

Figure 3-12. Cost Reductions of Three Advanced Technology Scenarios, Compared to Baseline Cases without Advanced Technology (Adapted from: Placet et al. 2004).

Note: Cumulative emissions (shown in the bar graphs) are highest when the emissions constraint is least stringent (750 ppm). Costs (line graphs) are highest when the emissions constraint is most stringent (450 ppm). Costs are lower (light blue, red and green lines) when advanced technology was assumed to be available, than when technology was assumed to advance only incrementally (dark blue line)

in the baseline scenario where technology advanced, but at rates more typical of historical experience.[32] Accumulated over the course of the 21st century, the potential economic benefits of such an advanced technology strategy, even without knowing which technologies would eventually emerge as most successful, would likely be significant.

Other studies in the literature reach similar conclusions. For example, Manne et al. (2004) examined limiting global temperature rise using scenarios with "optimistic" technological assumptions (i.e., assuming advanced technologies, such as fuel cells and integrated gasification combined cycle with CO_2 capture and storage, are available), compared to more "pessimistic" scenarios without such advanced technologies. The estimated costs[33] were estimated to be 2.5 times lower in the optimistic case than the pessimistic case. In another study, Edmonds et al. (2004) report that when a suite of advanced technologies (such as carbon capture and storage, biotechnology and hydrogen energy systems) are available to be

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[32] In this study, technology advancement was assumed to lead to more efficient energy technologies with lower capital and operating costs. Details on the assumptions can be found in Placet et al. (2004). The resulting cost reductions do not consider the cost associated with performing any R&D that might be necessary to achieve the improved technology performance.

[33] In the study, costs included those associated with fuel switching (to fuels or technologies with lower emissions), changes in domestic and international fuel prices, and price-induced conservation activities.

deployed at a large scale, the effective “tax” on GHG emissions that would be required to achieve the assumed reduction was 60 percent lower than when the advanced technologies were not available.

Other studies that explore the dynamics of technical change (e.g., Manne and Richels 2004, van Vuuren et al. 2004) show lower total abatement cost or lower mitigation costs through deployment of advanced technology. One of the major conclusions drawn at the recent IPCC Expert Meeting on Emission Scenarios was: “Technological change is fundamental for (reducing) stabilization (costs).”[34]

3.5.3 Key Technology R&D Areas

Review of scenario analyses indicates that, given the scale of the challenge, no single technology or class of technology would be likely to provide, by itself, the quantity of GHG emissions reductions needed to achieve most of the stabilization levels typically hypothesized and examined in the technology scenarios literature. Instead, these studies show that under a wide range of differing assumptions and planning uncertainties, technological advances aimed at the following four broad areas are likely to be needed *in combination* in order to contribute to the needed GHG emissions reductions: [35]

1. Energy End Use and Infrastructure
2. Low- and Zero-Emissions Energy Supply
3. CO_2 Capture/Storage and Sequestration
4. Non-CO_2 Greenhouse Gases

3.5.3.1 Energy End-Use Efficiency

Ultimately, global CO_2 emissions are driven by the demand for services (heating, cooling, transportation, etc.) that energy can provide. Technological advancement that can reduce the energy required to meet these services is one of the key levers for reducing GHG emissions. Scenarios analyses suggest that increased use of highly energy-efficient technologies and other means of reducing energy end use could play a major role in contributing to cost-effective emissions reduction within any given energy supply strategy.

In published scenarios, increasing demand for energy services, driven by population and economic growth, drives growth in GHG emissions over the 21st century. If gross world product were to grow by only 2.0 percent/year over the 21st century, and the demand for energy services were to grow at a commensurate 2.0 percent rate, then energy demand would grow seven-fold over the course of the century. Many published scenarios assume gross world product growth well above these rates. For example, at the top of the range of the IPCC’s *Special Report on Emissions Scenarios (SRES)* scenarios, gross world product grows at over 3.0 percent/year from 1990 through 2100.

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[34] Meeting Report of the IPCC Expert Meeting on Emission Scenarios, 12-14 January 2005, Washington DC. http://www.ipcc.ch/meet/washington.pdf

[35] CCTP also includes two supporting technology areas. These are measuring and monitoring technologies, and application of basic science to applied technology R&D. These supporting areas are not discussed in this chapter, though they are integral elements of the overall CCTP technology strategic plan.

However, in virtually all published scenarios, the demand for final energy[36] and, therefore, the emissions of CO_2 grow at a rate lower than gross world product growth, because improvements in end-use efficiency, along with structural economic changes, drive down the energy requirements associated with increasing global prosperity.[37] In 1990, global final energy intensity (energy used per dollar of gross world product) was roughly 17 billion joules per dollar. In the IPCC's *SRES* scenarios, final energy intensities in 2100 ranged from 1.4 billion joules per dollar of GDP to 5.9 billion joules per dollar of GDP.[38] Without these reductions in energy intensity, which are significant, energy demand growth, and therefore GHG emissions, would be significantly higher. This point is illustrated in Figure 3-13, which shows the relationship between global CO_2 emissions and final energy consumption in 2100 in the *SRES* scenarios. Although Figure 3-13 shows variation across multiple scenarios, in general, the greater the demand for final energy, the higher the CO_2 emissions and the more challenging the task of stabilizing CO_2 concentrations.[39]

This context demonstrates the benefits that would accrue from increasingly efficient end-use technologies. If R&D efforts were to increase the rate of final energy intensity improvement by only a

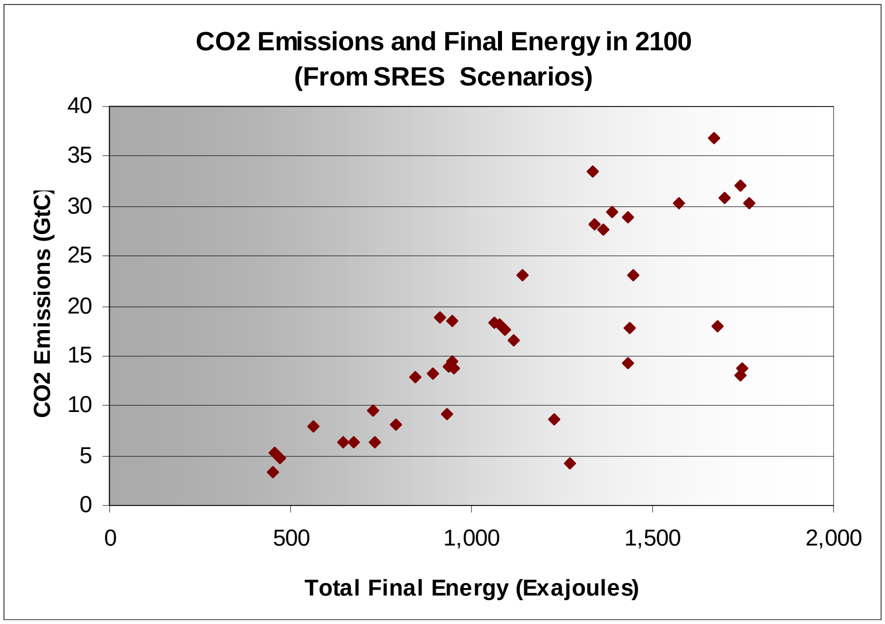

Figure 3-13. Relationship between CO_2 Emissions and Final Energy in the IPCC *SRES* Scenarios

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[36] Final energy refers to energy used at the point of end-use as opposed to energy used as an input to, for example, electricity generation. Final energy is lower than primary energy, because primary energy includes the efficiency losses required to transform primary energy to final energy.

[37] See the Greenhouse Gas Emissions Scenario Database at http://www-cger.nies.go.jp/cger-e/db/enterprise/scenario/scenario_index_e.html

[38] Range based on the illustrative scenarios from IPCC (2000).

[39] Variations in the relationship are due to, among other things, differences in final energy mixes (e.g., ratio of electricity, solid, liquid, and gaseous fuels) and the deployment of zero-emitting technologies. Note that these scenarios all assume no attempts to constrain carbon emissions.

quarter of a percent/year over the 21st century in a “middle-of-the-road” scenario, the required CO_2 emissions reductions would decrease by 3.5 GtC/year by 2100. This is roughly half of the total global CO_2 emissions today.[40]

Several scenario analyses point to the benefits of developing and deploying advanced end-use technologies. For example, the advanced technology scenarios in the recent PNNL report on climate change technology strategies assumed that advanced energy-efficiency technologies decreased final energy requirements by ten percent globally by 2100 (Placet et al. 2004). These reductions alone were responsible for a decrease of roughly 2.0 GtC/yr by 2100, in a scenario without any climate-change-related initiatives. Energy-efficiency improvements were also a critical driver of the decreased costs of stabilization across the board in these scenarios. Similarly, the IPCC’s *SRES* included a scenario (A1T) with advanced end-use technologies. In the simulation of this scenario using the Asian Pacific Integrated Model (AIM), the reductions from end-use efficiency alone (through reduced final energy intensity) were responsible for roughly 4.0 GtC/yr by 2100.[41] Hanson and Laitner (2004) incorporated advanced end-use technology assumptions, along with advanced supply-side assumptions and a range of policy levers to encourage technology deployment and reduce emissions, into the AMIGA integrated assessment model. In this study, approximately one-third of the U.S. carbon emissions reductions in 2050—roughly one GtC—are due to the deployment of more efficient end-use technologies.[42]

Providing technological options to reduce the energy required for production of goods and services demanded in a growing global economy can provide a fundamental way to achieve emissions reductions and lowering the need for GHG-free energy supply. This is true across the full spectrum of technology futures—whether these futures emphasize fossil fuels combined with CO_2 capture and storage, renewable or nuclear power, or novel technologies such as fusion and advanced bio-technology.

3.5.3.2 Low- and Zero-CO_2 Energy Supply Technologies

Supplying the world’s energy needs while achieving substantial reductions in GHG emissions may also require large contributions from energy supply technologies with near-zero emissions. These include renewable sources of electricity, such as wind, solar and hydroelectric power, biomass-based energy systems, and nuclear power, as well as the use of these technologies to produce hydrogen. These could also include novel advanced technologies such as fusion and advanced biotechnologies.

A number of scenario analyses have shown the importance of low- and zero-energy supply technologies in reducing emissions to achieve a given climate policy through the use of integrated assessment models. For example, Akimoto et al. (2004)[43] show that for a hypothetical climate policy, the share of the world’s primary energy in 2100 met by biomass and wind energy increased by more than 70 percent from their

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[40] This calculation is based on the illustrative B2 scenario from IPCC (2000). It assumes that lower final energy requirements would not alter the relative proportions of energy provided from different sources.

[41] Result based on the illustrative scenarios for the A1 set. It was calculated based on a comparison of the illustrative A1T scenario with the illustrative A1B scenario, assuming no change in the primary energy mix between the two. While not identical to A1T, A1B is similar in terms of the emissions per unit of primary energy and therefore serves as an effective reference.

[42] Note that many of the assumptions in this study followed from the study, *Scenarios for a Clean Energy Future* (see Brown et al. 2001).

[43] The study used an updated version of the DNE21 model, an integrated assessment model which hard-links macroeconomic, energy systems, and climate change models, and seeks optimal development of the world’s energy system for a given climate policy based on maximizing macroeconomic consumption.

reference case contributions of 10 percent and 4 percent, respectively. In addition, solar power supplied almost 5 percent of the world's primary energy demand by 2100,[44] and nuclear, biomass and renewable energy accounted for about 30 percent of the emissions reduction in 2100, in approximately equal shares. Similarly, Edmonds et al. (2004) report increasing contributions from solar and nuclear energy under carbon constraints, especially when fossil-based generation technologies and CO_2 capture and storage technologies are not assumed to advance.[45]

As discussed in previous sections, Placet et al. (2004) examined several advanced technology scenarios to achieve a range of emissions reduction targets. Low- and zero-emissions energy technologies (including solar, wind, biomass, nuclear fission, and novel concepts such as nuclear fusion and advanced biotechnology) contribute between 23 percent and 34 percent of world primary energy demand by 2100, depending on the scenario.

In several scenarios, renewable sources are also important sources for generating hydrogen and other secondary fuels for different end-use sectors. For example, Edmonds et al. (2004) show that, under a medium carbon constraint, the preferred feedstock for hydrogen production switches from fossil feedstock to biomass, because the application of carbon dioxide capture and storage (CCS) to biomass-based H_2 production can have net negative emissions. Alternatively, Mori and Saito (2004) report that H_2 production from fast breeder reactors can supply nearly all of the final energy demand for hydrogen and can be a cost-effective way to achieve significant emissions reductions.[46]

3.5.3.3 Carbon Capture/Storage and Sequestration

The CCTP technology area related to capturing and sequestering CO_2 has two main thrusts: (1) engineered capture and storage of CO_2 from power plants and other industrial sources of CO_2 emissions, and (2) terrestrial sequestration of CO_2 in trees, soils, and other terrestrial systems.

3.5.3.3.1 Capture and Storage of Carbon Dioxide

Carbon dioxide capture and storage (CCS) refers to the capture of carbon dioxide emitted from power generation or industrial processes, and subsequent storage in suitable deep geologic or deep ocean reservoirs. The benefits of CCS technologies stem from their ability to continue to make use of abundant and therefore relatively inexpensive fossil energy resources while simultaneously delivering substantial and sustained CO_2 emissions reductions. CCS could also be applied to bio-based electricity-generation systems.

A number of recent studies using integrated assessment models have examined the potential of CCS to lower future CO_2 emissions. For example, Edmonds et al. (2004) report that fossil energy technologies with CCS can supply approximately 55 percent of the global electricity generation by the end of the

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[44] The upper limit of the world total nuclear production assumed in this scenario was 920 GW in 2050 and 1450 GW in 2100, so nuclear energy was not a major contributor in this analysis.

[45] This study used the MiniCAM model and the IPCC *SRES* B2 Scenario to examine the role of advanced technologies under a climate policy aimed at stabilizing atmospheric CO_2 concentrations at 550 ppmv.

[46] This study used the MARIA integrated assessment model to examine the role of nuclear technology and hydrogen use under different climate policies, and different technology advancement assumptions.

century in an advanced technology scenario with high emissions reductions.[47] This was more than twice the contribution as compared to a modeling case when CCS (and other advanced energy technologies) were not assumed to advance as rapidly. McFarland et al. (2004) find fossil-based power systems with CCS account for approximately 70 percent of global electricity production under a high GHG emissions constraint, when CCS systems and other advanced fossil energy systems are allowed to deploy to their full market potential, as compared to ~10 percent under a reference scenario with no climate policy.[48] Placet et al. (2004) show fossil systems with CCS contributing up to 50 percent more of the world's total primary energy consumption in 2100 in scenarios featuring technology advancement in CCS and fossil generation, as compared to scenarios where advancement occurs in other types of technologies.[49]

Several studies have also examined the economic implications of using CCS, either in isolation or along with other technological advancements. By allowing for abundant fossil energy stocks to be used while simultaneously delivering reductions in CO_2 emissions, CCS technologies help to constrain the rate of increase and ultimate peak of carbon prices (an indication of the overall cost of achieving the emission reductions[50]). For example, Edmonds et al. (2004) show that, through the large-scale adoption of CCS and other advanced fossil energy technologies, peak carbon permit prices were 62 percent lower than if those technologies were not allowed to deploy to their full market potential. In the study by McFarland et al. (2004), CCS reduces carbon prices by 33 percent at the end of the century.

While the studies summarized here use comparable costs for CCS (especially in their advanced technology scenarios), they employ different modeling approaches, technology representations and climate policies. However, they have all shown that CCS has the potential to play a significant role in emissions mitigation during the 21st century, and that technology advancement magnifies this contribution while delivering substantial economic savings. Early technical resolution of the viability of various CCS options could have significant implications for subsequent R&D investment strategies.

3.5.3.3.2 Terrestrial Sequestration

Land-use change that results in net CO_2 release to the atmosphere accounts for about 22 percent of today's global CO_2 emissions (IPCC 1996). At the same time, terrestrial systems in many parts of the world are being managed in ways that remove carbon from the atmosphere and sequester it in soils and biomass. Over the next several decades the potential exists to achieve significant reductions in global CO_2 emissions by managing the world's terrestrial systems to accumulate and store additional carbon.

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[47] This analysis used the PNNL MiniCAM model, with implementation of the IPCC SRES B2 scenario was used as the reference case, and compared with an advanced technology case with more efficient and economical CCS, higher efficiency fossil generation, and hydrogen energy systems, to examine the role of advanced technologies like CCS in a stabilization strategy.

[48] This study used the MIT EPPA model, a recursive dynamic multi-regional general equilibrium model of the world economy. Bottom-up information about coal and natural gas based generation systems with CCS were used in a top-down energy economics model to examine the effect of CCS on different climate policies.

[49] This study used the PNNL MiniCAM model to examine energy and economic implications of different technology futures and different levels of emissions reductions. One future assumes CCS technologies meet aggressive technical, economic, and environmental goals for application on fossil and biomass-based energy systems, along with higher-efficiency fossil generation and greater end-use efficiency gains.

[50] Since the cost of compliance is the total area under the marginal abatement curve, the last two metrics are strongly correlated i.e., the higher the reduction in the carbon price, the greater the reduction in the cost of compliance.

How much of this potential can be realized, however, is very uncertain and will depend on the development and diffusion of advanced technologies in a variety of economic sectors.

Globally, the goods and services derived from land resources—including food, water, shelter, energy, and recreation—are basic to human existence and quality of life. One insight that has emerged in the literature on long-run GHG emissions scenarios is that future changes in cropland, grassland, and forest land areas—regionally and globally—will be driven by the ability of land resources to provide these basic goods and services. Hence, the potential to use terrestrial systems to sequester carbon and mitigate global GHG emissions will be directly affected by the development of advanced technologies that reduce human pressures on land by increasing land productivity across a range of economic sectors—including (but not limited to) agriculture, forestry, and energy.

In agriculture, advanced technologies could enhance terrestrial carbon sequestration by enabling the development of new food and fiber products, production processes, and distribution systems that reduce the amount of land needed to feed and clothe the world's population. In forestry, advanced technologies could accelerate the processes of reforestation and afforestation, as well as increase the quantity of wood products that could be obtained from a unit of forest land. Advanced energy technologies could increase terrestrial sequestration by reducing deforestation pressures in developing countries and shifting cropland to bioenergy crop systems that not only increase soil carbon levels but also shift energy production toward technologies that recycle atmospheric CO_2.

In the absence of any human intervention, Sohngen and Mendelsohn (2003) suggest that global forests have a net sequestration potential of about 18 GtC in the coming century (see Section 3.2.1.2). In a more recent study performed as part of EMF-21, this potential was projected to increase by an additional 48 to 147 GtC by 2100 under different climate policies (Sohngen and Sedjo forthcoming). The cost of land-use and forest sequestration has been estimated to range between $10-$200 per ton of carbon stored (Richards and Stokes 2004).

3.5.3.4 Non-CO_2 GHG Emissions

Non-CO_2 GHGs play an important role in the CCTP framework because of the high reduction potential over the next 100 years and the potential for reducing the overall cost of stabilization. These gases are particularly important because a variety of scenario analyses show that a significant level of reduction is achievable in the first half of the 21st century.

Potential reductions and cost savings are illustrated in the Energy Modeling Forum multi-gas scenario study – EMF-21 (Weyant and de la Chesnaye 2005), and other long-term multi-gas studies (e.g., Manne and Richels 2000, 2001; Reilly et al. 2002). The various models exercised in the EMF-21 study used a range of assumptions about technology development, leading to a range of reductions of non-CO_2 GHGs. The studies suggest that, between 2000 and 2100, emissions of non-CO_2 "well mixed" gases (methane, nitrous oxide, and the fluorinated gases) in a moderately constrained case[51] could be reduced by as much as 48 percent, and the cost of stabilization could be lowered by 30 to 60 percent compared to a CO_2-only scenario.

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[51] The constrained case was defined as 4.5 W/m^2 stabilization target by 2100.

In addition to the long-term EMF-21 multi-gas scenarios, two other studies illustrate maximum technology potential of non-CO_2 mitigation options over the medium term. Delhotal and Gallaher (2005) projected the reduction potential of technological improvements out to 2030 in the three major methane emitting sectors—landfills, natural gas, and coal—for selected countries. By 2030, cost-effective technologies could reduce methane emission to less than 50 percent of current levels in the United States, and could potentially reduce emissions by a factor of two in countries such as China, Mexico, and Russia in the same time frame. Another study by the International Institute for Applied Systems Analysis (IIASA) (Cofala et al. 2005) shows the "maximum potential reductions" out to 2030. This study concluded that if all currently available technologies were applied to landfills, agriculture, the natural gas sector, the coal sector, and oil and gas extraction, without consideration of cost, global CH_4 emissions would stabilize and continue to be stable up to 2030.

The scenario analyses above do not explicitly include new non-CO_2 mitigation technologies. An analysis conducted by the U.S. Environmental Protection Agency in cooperation with PNNL assumed the development of advanced technologies in areas such as methane emissions from waste and energy sectors, methane and nitrous oxide emissions from agriculture, and high-GWP emissions from the industrial sector (Placet et al. 2004). Compared to a reference scenario with no emissions constraints and no new non-CO_2 mitigation technologies, the study suggests that reductions in emissions from other GHGs could potentially contribute 120 to 160 GtC-eq in cumulative emissions reductions over the century. The assumptions underlying the advanced technology scenario are based on the currently known methods to achieve emissions reduction, as well as detailed "bottom-up" analyses of the technical potential to reduce non-CO_2 GHGs further. Results from this analysis for a high carbon-constrained case are shown in Figure 3-14.

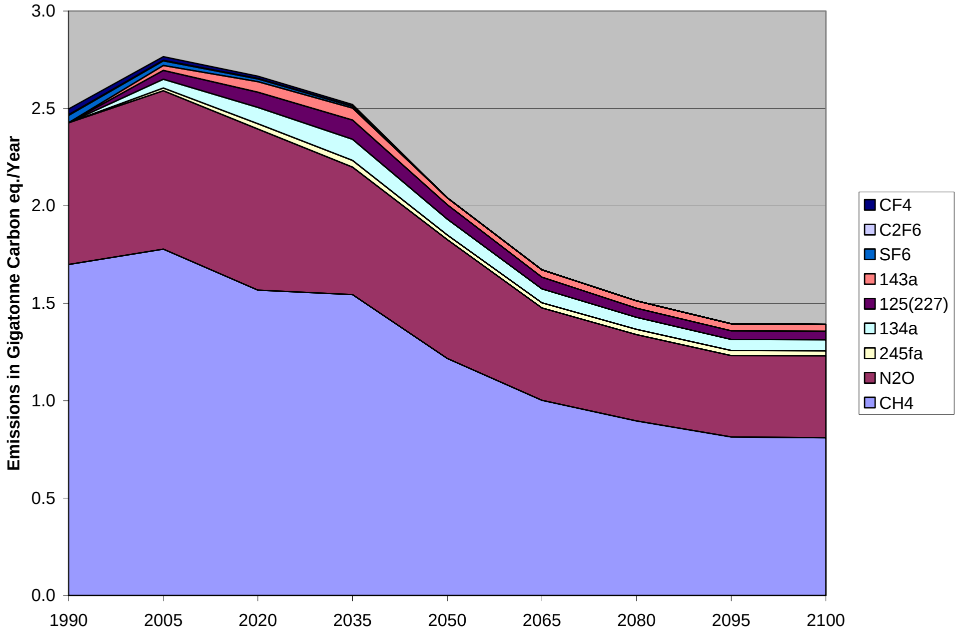

Figure 3-14. World Non-CO_2 GHG Emissions in a High Carbon-Constrained Case[52]

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[52] This figure was based on the *A New Energy Backbone* scenario (Scenario 2).

3.5.3.5 Summary: Relative Contributions of the Four CCTP Goals

As described in the sections above, a variety of scenarios analyses conducted by different research groups show the importance of technology advancement consistent with each of the four core CCTP emissions-reduction goals:

1. Reduce emissions from energy end use and infrastructure
2. Reduce emissions from energy supply
3. Capture and sequester CO_2
4. Reduce emissions of non-CO_2 greenhouse gases

In general, scenario analyses typically indicate that no single technology option is able to provide sufficient emissions reductions to meet stabilization objectives.

This point is illustrated by the results of the PNNL study, in which each of the four technology areas was shown to make contributions toward stabilizing concentrations. Based on the assumptions used in this set of scenarios, no one area was markedly more or less important than others. Figure 3-15, redrawn from

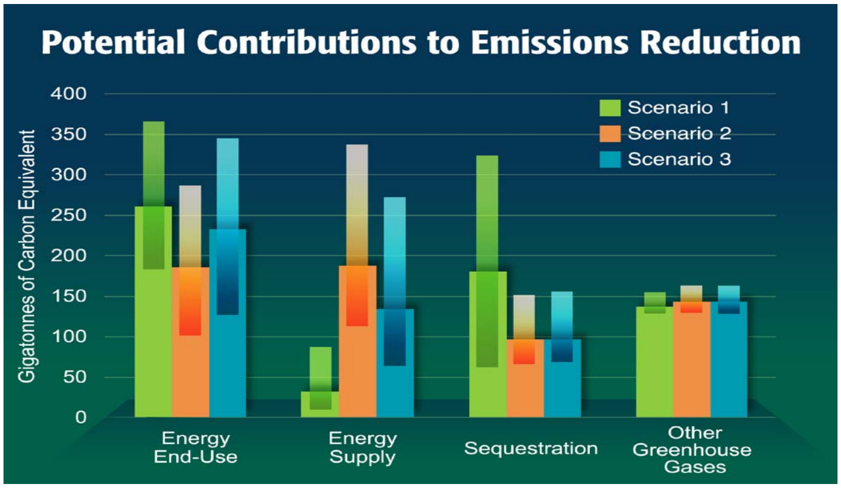

Figure 3-15. Cumulative Contributions between 2000 and 2100 to the Reduction, Avoidance, Capture and Sequestration of Greenhouse Gas Emissions for the Three Advanced Technology Scenarios, Under Varying Carbon Constraints[53]

Note: The thick bars show the contribution in the high emission reduction case and the thinner bars show the variation in the contribution between the very high emission reduction case and the low emission reduction case.

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[53] The figure shows the cumulative contributions between 2000 and 2100 to the reduction, avoidance, capture/ storage and sequestration of greenhouse gas emissions under the three Advanced Technology Scenarios, based on varying emissions constrained cases. The thick bars show the contribution under the high emission constraint and the thinner, semi-transparent bars show the variation in the contribution between the very high emissions constraint and the low emissions constraint. "Energy End-Use" includes emission reductions due to energy efficiency measures. "Energy Supply" includes emissions reductions from the substitution of non-fossil energy supply technologies with low or zero CO_2 emissions for fossil-based power generation without capture and storage of CO_2. "Sequestration" includes carbon capture and storage from fossil-based technologies, as well as terrestrial sequestration.

that analysis, shows the contributions of four technology categories (directly linked to the four CCTP goals stated above) to cumulative GHG emissions reductions over the 100-year scale, across a range of different scenarios. The figure represents one set of possible scenario outcomes based on a particular set of assumptions about advanced technologies over the next century. It offers a glimpse of the range of emissions reductions new technologies might make possible through reduced energy end use; low-or zero-emission energy supply; carbon capture, storage and sequestration; and reduction of other greenhouse gases – on a 100-year scale and across a range of uncertainties.

3.6 Summary of Insights

Many studies have examined long-term GHG emissions trends under a range of assumptions about the rate of change of population, economic growth, and technology change, and the potential role for advanced technology in mitigating emissions growth. Although the rate of GHG emissions growth over the 21st century is uncertain and will depend on many variables, the synthesis assessment of scenarios analyses suggests that significant increases in GHG emissions are projected in most scenarios that assume no specific climate-change-related initiatives. Further scientific study must be undertaken to determine the amount and timing of emissions reductions that would be needed to stabilize concentrations at a level that would prevent dangerous anthropogenic interference with the climate system. Many scenarios analyses have shown that the necessary cumulative emissions reductions over the course of the century could be on the order of 200 GtC-eq to 800 GtC-eq (or more).

Emissions reductions of that scale potentially could be achieved through combinations of many different technologies. A large number of scenarios analyses conducted by different research groups show the importance of technology advancement in each of the four core CCTP technology areas. An important insight that can be drawn from these studies is that under a wide range of differing assumptions, advanced technologies associated with energy end use; energy supply; carbon capture, storage and sequestration; and controlling emissions of non-CO_2 GHGs could all potentially contribute significantly to overall GHG emission reductions. This suggests the importance of a diversified approach to technology R&D.

Scenarios analyses also suggest that successful development of advanced technologies could result in potentially large economic benefits. When the costs of achieving different levels of emission reductions were compared for cases with and without advanced technologies, many of the advanced technology scenarios projected that the cost savings would be significant over the course of 100 years.

Finally, scenarios analyses suggest that the timing of the commercial readiness of advanced technology options is an important planning consideration for all scenarios, and particularly for the tighter GHG emissions constraints. Looking over a 100-year planning horizon, and allowing for capital stock turnover and other inertia inherent in the energy system, technologies with zero or near-net-zero GHG emissions would need to be available and moving into the marketplace many years before the emissions “peaks” occur in the hypothetical GHG-constrained cases. Allowing for appropriate lead-in periods for technology development and commercialization, in most of the GHG-constrained cases, some new technologies may need to be commercially ready for widespread implementation between 2020 and 2040, with initial demonstrations between 2010 and 2030.

The following chapters focus in depth on various technological means for making progress toward, and eventually achieving, each of the CCTP strategic goals. Guided, in part, by the insights gained through the review and synthesis of the scenarios analyses, each chapter’s discussion addresses the rationale and technology strategy that would guide investments in the current technology portfolio and identifies candidate areas for future research directions that could accelerate technology development and contributions to CCTP goals.

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